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A SYSTEMS PLAN FOR AN EARTH AND OCEAN DYNAMICS SATELLITE APPLICATIONS PROGRAM

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Joseph W. Siry

SUMMARY

The promise of lasers capable of measuring range with decimeter accuracy and electronic tracking systems and VLBI equipment having comparable performance has opened up the exciting prospect of investigating many phenomena associated with the Earth's dynamical and crustal motions and sea surfaces which are not only scientifically interesting but may also be of real value from the applications standpoint as well. The present state of the art is one or two orders of magnitude or more away from these levels due largely to limitations in our knowledge of the Earth's gravitational field and figure. The main purpose of this discussion is to look at these various matters from a unified point of view and to consider a coordinated set of approaches for attacking these intriguing problems.

The proposed observing systems include the following facilities.

1. A network of fundamental stations, indicated in Figure 1, whose locations and motions, including polar, UT 1, and crustal motions, are determined by VLBI, relative to the basic reference system of radio stars. The sites are all NASA Goddard stations with the exception of Kashima, Japan, a facility which has participated extensively in the ATS program.

2. A system of Geopause spacecraft in nearly circular polar orbits, normal to the ecliptic at a distance of about 5 earth radii with a period on the order of two thirds of a day.

The Geopause spacecraft are tracked by laser and electronic range and range rate tracking systems collocated with the VLBI systems at the fundamental stations. They will also carry VLBI sources. This will permit direct intercomparison of results obtained from the three systems.

The polar orbit provides good geometry for polar motion studies and eliminates secular perturbations due to zonal harmonics. Lunisolar perturbations to the inclination are minimized by placing the orbit normal to the ecliptic.

The altitude of the Geopause orbit is chosen so that the number of gravitational harmonic coefficients whose estimated uncertainties correspond to perturbations larger than a decimeter is reasonably small. This makes it feasible to solve for them along with the orbit elements and other environmental parameters such as those associated with GM and a detailed model of the radiation pressure effect.

The altitude also permits viewing from at least one of the fundamental stations at almost all times, and simultaneous observing from 3 or more of the fundamental stations and 4 or more ranging systems on many occasions, making it possible to solve directly for tracking system biases.

The period is chosen sufficiently different from 12 or 24 hours, e.g., from 14 to 20 hours, say, to take advantage of the high visibility property by insuring that observations of the Geopause satellite will provide good geometrical coverage at all the fundamental stations, permitting accurate determination of their locations and motions, such as polar motions, in reasonably short time intervals, i.e., a few days for station locations, and a day or less for a polar motion component.

The orbital characteristics of the Geopause satellite and the nearly continuous data sets obtained by tracking it from the fundamental stations will thus permit, for the first time, the determination of the unknown quantities associated with all the important aspects of the problem, i.e., gravitational and radiation pressure perturbations, station locations and motions, and tracking system biases.

Fundamental station locations and polar and crustal motions can be studied using both VLBI and the Geopause spacecraft. The main contribution of VLBI is to provide the ultimate fundamental inertial reference based on the radio sources, which is important for studying the earth's dynamical and crustal motions over long periods of time, e.g., years. Laser and electronic range tracking of the Geopause spacecraft can provide the high densities of accurate data in short time periods which are needed to observe fine structure in the polar motion and in crustal deformations near faults. Studies of these phenomena and correlations among them and earthquakes may lead to the possibility of making earthquake risk predictions. Mobile laser, VLBI or ranging facilities can be located at the various sites of special geophysical interest such as those associated with studies of tectonic plate motion in 1 and 3 dimensions, the San Andreas Fault Experiment (SAFE) Project, etc. (Cf. **Figs. 2 & 3.**) The Geopause spacecraft and the Fundamental Network provide a 2-hemisphere capability for observing polar motion which should be of value in this connection.

The Geopause spacecraft is the ideal high-altitude terminal for satellite-to-satellite tracking of Drag-free and altimeter satellites at about 250 to 350, and 700 km altitudes, respectively. These low-altitude satellites should be placed in orbits having the same plane as the Geopause orbit. Radial and along-track components of the Drag-free satellite's velocity are observed, respectively, near the sub-Geopause point, and the Earth's limbs. The Drag-free satellite completes about eight revolutions during each revolution of the Geopause. Thus each 45 minute satellite-to-satellite tracking pass centered on the sub-Geopause point is displaced from the previous pass by about 45° in latitude and 24° in longitude. By choosing the commensurabilities properly, a sampling of the entire gravitational field and hence the geoid can be completed with a resolution equal to the Drag-free satellite height, i.e., about 3°, in half a year or so. Such a survey using an 0.03 mm/sec tracking system should form the basis for a geoid of decimeter accuracy.

Two Geopause spacecraft in the same orbit but separated by about 90° in mean anomaly can observe 2 in-plane components of position and velocity of Drag-free and altimeter satellites in the prime coverage arc spanning a quarter of a revolution of the low-altitude spacecraft. (Cf. Fig. 6.) Thus, for example, the radial distance of the altimeter and hence the ocean surface can be found. The along-track and radial velocity components of the Drag-free satellite can also be derived simultaneously, permitting a better solution for the gravity field and the geoid in less time. This two Geopause spacecraft system is thus the key to determining the geoid and the ocean surface independently with accuracies approaching the decimeter instrument capabilities to within half an order of magnitude or so. Four Geopause spacecraft can provide continuous, synoptic monitoring of the ocean surface height on an operational basis.

A possible configuration for the Geopause spacecraft is indicated in Fig. 7. It could be stabilized by means of a gravity gradient system similar to the one proposed for the stabilization experiment which was once approved for ATS-F.

These and other related aspects of the program, including lunar planetary studies, are discussed in more detail in the main body of the report.

A SYSTEMS PLAN FOR AN EARTH AND OCEAN DYNAMICS APPLICATIONS PROGRAM

by

Joseph W. Siry

I. INTRODUCTION

The Earth Physics and Geodesy Program has a number of important scientific goals and potential applications. New approaches are becoming available for achieving these aims and applying the advanced capabilities in practical ways. The goals and applications can be indicated briefly as follows.

A. Goals

Among the goals are the generation of new knowledge concerning:

1. The earth's gravitational field
2. The geometrical characteristics of the earth
3. The dynamical motions of the earth as a whole
4. The active earth including tectonic plate motions, continental drift, and earthquakes
5. Related dynamics of the Earth-Moon system, and
6. Other correlative disciplines including geomagnetism, atmospheric structure, the ionosphere, etc.

B. Applications

One looks forward, as the state of the art advances sufficiently, to the possibility of applying the fundamental scientific knowledge gained in these ways to the solution of practical problems associated with:

1. Earthquakes
2. Ocean currents
3. Surveys, e.g., in marine regions such as continental shelves, and
4. Gravity anomalies, e.g., those associated with deposits.

These points are discussed further in references 1 & 2.

The following kinds of investigation techniques, orbits and experiments are potentially useful.

C. Investigation Techniques

New methods of investigation are now at hand for use in achieving these scientific goals and applications objectives.

They include:

1. Advanced laser tracking
2. Advanced electronic range and range rate tracking
3. Satellite-to-satellite tracking
4. Satellite altimetry
5. Very long baseline interferometry (VLBI)
6. Lunar laser and beacon systems

D. Orbits and Experiments

A variety of orbits and experimental configurations are available. These include one or more spacecraft in:

1. Conventional geodetic orbits at about 1000 km. altitude
2. Synchronous orbits
3. Low altitude drag-free orbits
4. Intermediate altitude orbits, and
5. Lunar and planetary orbits,

as well as

VLBI systems, and

Lunar laser and beacon systems.

The purpose, here, is to consider these various program elements and their potential interrelationships from a unified standpoint. The discussion is organized along lines indicated by scientific and technological considerations. Accordingly, the early parts of the discussion do not necessarily reflect or imply any proposed chronological order. Matters relating to schedules, etc., will be addressed later.

II. INVESTIGATION APPROACHES

This discussion of various possible investigation approaches begins with fundamental reference systems and the earth's dynamical and crustal motions including continental drift and other movements of its tectonic plates.

A. Fundamental Reference Systems and Dynamical and Crustal Motions

1. Very Long Baseline Interferometry

a. Fundamental Station Locations

We have, to begin with, the radio sources, or quasi-stellar objects (QSOs) as they are sometimes called, which presumably have even less proper motion than the "fixed" stars of conventional optics. It appears, on the basis of the promising resolution capability of the new interferometers and the small apparent diameters of the QSOs, that it should be possible to determine the locations of observing sites more accurately with VLBI than with optical telescopes. For example, resolution results have been reported at the level of a thousandth of a second of arc. (Cf. reference 3) Hence, certain VLBI sites can become fundamental stations of the Earth Physics and Geodesy Program. Their positions and motions relative to the ultimate reference system consisting of the QSO's provide a framework for the program. A possible initial set of fundamental stations is indicated in Table 1 and Figure 1.

b. Dynamical and Crustal Motions

Knowing the fundamental positions as functions of time one has, in principle at least, information about the dynamical motions of the earth as a whole, and the motions of tectonic plates on its surface, i.e., about precession, nutation, polar motion, variations in the earth's rotational rate, i.e., UT1, continental drift, etc.

A configuration of the type indicated in Table 1 and Figure 1 could provide a basic reference system, information about polar motion and UT1, and some continental drift data.

Further plate motion studies in one dimension can be conducted in the Pacific area with the aid of the additional stations indicated in Table 2 and Figure 2.

In order to study the motions of tectonic plates in three dimensions, additional stations would be needed. Possible locations for three-station nets in America and Europe are indicated in Table 3 and Figure 3. Some antenna capability already exists at these sites. A complete VLBI study of such tectonic plate motions would involve nets similar to those of Table 3 and Figure 3 for each plate. This point will be discussed further later.

The VLBI locations shown in Tables 1, 2, and 3 and Figures 1, 2, and 3 are illustrative. Clearly, there exist other alternatives which depend upon the availability of antennas, etc. (Cf. Fig. 4.)

In summary, it appears that the primary contribution of the VLBI technique will be to provide the basic inertial reference data. The method is thus especially suited for studies involving long time constants such as, for example, those associated with precession, nutation, continental drift and other tectonic plate motions. A complete VLBI study of crustal motions could be expensive. An optimum strategy for attacking this problem probably will involve the use of both VLBI and ranging systems of the laser and electronic type. Practical limitations connected with the frequency and duration of the observing intervals may also restrict the utility of VLBI as a means of observing fine structure in the polar motion and UT1, including features associated with earthquakes, for example.

2. Satellite Reference Systems

It appears to be practical to develop laser and electronic ranging systems having resolution and accuracy comparable with that of VLBI systems. Observations of suitably equipped satellites, including the moon, can furnish the basis for studies of the same types as those which are contemplated in the VLBI program.

The principal limitation on the full use of laser and electronic ranging systems is the lack of sufficiently accurate knowledge of those motions of the observed object which could affect the observations. Nothing comparable to the QSOs of the VLBI system exists at the moment. The orbits of laser corner reflector satellites are perturbed by harmonic components of the Earth's gravity field. Uncertainties in the motions of geodetic satellites corresponding to uncertainties in harmonic coefficients of the geopotential are at the level of five to ten meters under the best of circumstances and, as a practical matter, may frequently be an order of magnitude larger (Cf. reference 4).

It is proposed therefore to surmount this obstacle by selecting an orbit with the following properties:

1. Geopotential effects are reduced to a point where uncertainties in only a few coefficients result in satellite position uncertainties above the decimeter level.
2. Good geometrical coverage for station positioning is available for all stations in a relatively short time interval.

3. The satellite can be observed essentially continuously from a fundamental network such as that of Figure 1, much of the time from 3 or 4 more stations simultaneously, weather permitting, thus making possible:

   a. Good determination of any environmental parameters which may still have significant uncertainties, and

   b. Intercomparison and calibration of laser and electronic ranging systems whenever 4 or more stations observe at one time

4. Good coverage for polar motion and UT1 observations from a network of fundamental stations in both hemispheres, including the potential VLBI sites shown in Figure 1 and Table 1.

Present preliminary estimates indicate that an orbit having approximately the following characteristics will have the indicated properties:

Period	19 hours
e	0
i	90°
Ω	90°

Further study may point to an optimum orbit having somewhat different characteristics. The following discussion indicates reasons for the selection of the parameters listed and some alternative choices which may also be suitable.

Periods in the range from about 10 to 20 hours could also be useful. Periods above about 28 hours might also have value here. In these ranges the shorter periods are probably a little poorer from the standpoint of the geopotential uncertainties, and a little better from the standpoints of ranging distances and times required for good coverage.

Perturbations of inclination and node due to zonal harmonics are eliminated when $i = 90^{\circ}$.

Solar perturbations of the inclination are minimized when $\Omega = 90^{\circ}$. This appears to be an optimum choice for minimizing lunisolar effects over an interval of nine years or longer. Average lunisolar perturbations over a selected shorter interval can be made smaller by choosing a slightly different value for the node which will cause the lunar and solar effects on inclination to balance and cancel each other in a mean sense over the time interval of interest.

Uncertainties in radiation pressure effects can be minimized by better representation of the reflection characteristics of the satellite. This could involve measurements before flight, prediction of changes in reflective properties in the space environment and possibly the selection of materials whose reflection parameters would change in only a minimal way after the satellite is launched. An extreme solution to the radiation pressure problem would be to employ a (radiation) drag-free system, however it would be preferable to avoid such a complication.

Such an orbit, at the outer boundary of the region in which the uncertainties in the periodic geopotential effects are sensible, can be thought of as being at the geopause. The orbit of such a geopause satellite probably comes as close to being a purely Keplerian one as is practical from the standpoint of this discussion. It can be viewed as being in a region where the geopotential noise level is low.

The strategy for analyzing the geopause satellite observational data would involve solving for the orbital elements, the locations of the laser and electronic ranging stations, and any environmental parameters which appear to be significant. These might include the masses of the Earth, the moon, and the sun, one or more radiation pressure parameters, and a relatively small number of geopotential coefficients.

The properties of the orbit indicated in items 1 through 3 earlier in this section indicate that there is a reasonable likelihood of approaching a realization of the potential of the laser and electronic range system tracking accuracies.

The Geopause satellite system can provide good numbers of accurate measures of the distances between the satellite and each ground station in three directions which are approximately orthogonal at the station and which have reasonably good elevation angles. Thus, it should be possible to determine the radial distances of the satellite and the station locations with accuracies which are comparable with the laser and electronic tracking system accuracies to within a factor of two or so.

Further studies should give more detailed information about the capability of the GEOPAUSE satellite laser and electronic ranging systems, and indicate more specifically what the system characteristics should be. The actual use of such a GEOPAUSE satellite laser and electronic ranging system might, of course, reveal unforseen problems. The GEOPAUSE system does, however, appear to offer real possibilities for exploiting the potential of laser and electronic ranging for Earth Physics and Geodesy.

3. <u>A Fundamental Network of Combined VLBI and Satellite Observing Stations</u>

It is recommended that laser and electronic tracking systems be located at the fundamental stations indicated in Figure 1 and Table 1. Direct intercomparison of the station locations and motions determined independently by VLBI and by the GEOPAUSE satellite laser and electronic tracking systems will then be possible, thus making these truly fundamental stations of the Earth Physics and Geodesy Program.

Once the different systems have been mutually verified, stations of any one of the three types can be located at other sites for plate motion studies, etc.

The VLBI system and the GEOPAUSE satellite laser and electronic ranging systems complement each other nicely. VLBI provides the basic inertial reference accuracy over long periods, which is important for plate motion studies. A number of additional potential VLBI sites already exist, as is indicated in Figures 2 & 3 and Tables 2 & 3. Many of these are at Goddard ground stations. The VLBI capability can also provide the fundamental inertial reference system in terms of which the orbit of GEOPAUSE is specified.

The GEOPAUSE satellite laser and electronic ranging systems can readily provide high densities of accurate observations over relatively short time intervals. This is important for studies of the fine structures of the polar motion and UT1, and their correlations with earthquake phenomena. The GEOPAUSE satellite system ground stations involving laser and/or electronic ranging systems are probably also more suitable for use in sites where no equipment now exists. Thus they can play an important role in filling in gaps in the overall study of the relative motions of the major tectonic plates. They will probably also be especially useful in the study of intraplate motions, i.e., the deformations of plates near fault lines.

Such an experiment, for example, has been proposed for the San Andreas fault neighborhood. Professor L. R. Sykes is investigating the relative merits of candidate sites for the lasers. Two of them might, for example, be located a thousand kilometers apart on opposite sides of the fault about a hundred kilometers from it. The aim would be to detect movements in the far zone, i.e., at some distance from the fault. Deformations associated with earthquakes would be looked for. Stored energy estimates would be sought. Earthquake risk predictions would be hoped for. The project has been referred to as the San Andreas Fault Experiment Project, i.e., the SAFE Project. (Cf. reference 11.)

The GEOPAUSE spacecraft could also include a VLBI source, making possible further intercomparisons of observing systems collocated at the fundamental stations.

a. A Two-Hemisphere Latitude, Polar Motion and UT 1 Observation Network

At the present time, latitude and polar motion observations are made partly from a ring of stations around the parallel at $39^{\circ}\ 8'$. Their locations are indicated in Figure 5 and Table 5. It is seen that the Northern hemisphere stations of the fundamental network of Figure 1 and Table 1 are in the same regions as the latitude and polar motion service stations. The Fundamental Network has a second complete polar motion subnetwork in the Southern hemisphere which corresponds to, and complements, the one in the Northern hemisphere. The Southern network can thus provide valuable checks of the polar motion results obtained using Northern hemisphere stations.

4. Lunar Laser and Beacon Systems

Laser corner reflectors and beacons on the moon can be used to obtain information about the positions of stations on the Earth's surface referred to the lunar ephemeris. Analysis of lunar laser and beacon data to determine polar motion and UT 1 for the Earth will be intertwined with the analysis of the same data to determine corresponding librational motions of the moon.

B. Satellite Sea Surface Studies

An important element of the Earth Physics and Geodesy Program is the obtaining of ocean surface height information by means of satellite altimeters. A number of Earth Physics Applications require such ocean surface information with accuracies in the decimeter range. Knowledge of the altimeter satellite's position to corresponding accuracy will, accordingly, be necessary.

The GEOPAUSE satellite system has the type of capability which is ideally suited for this application. The altimeter satellite can be placed in an orbit having the same plane as that of the GEOPAUSE orbit. Satellite-to-satellite range tracking between the GEOPAUSE satellite and the altimeter satellite can provide independent information about the radial distance of the altimeter from the Earth's center when the altimeter spacecraft is generally beneath the GEOPAUSE satellite.

A great increase in coverage can be obtained through the use of a second GEOPAUSE satellite which is placed in the same orbit as the first one but separated from it in mean anomaly by 90° (Fig. 6.). The prime coverage arc for this system occurs when the altimeter spacecraft is between the two GEOPAUSE satellites, i.e., when its true anomaly is between theirs. Measures of the distances between each of the GEOPAUSE satellites and the altimeter spacecraft in the prime coverage arc give 2 components of the altimeter satellite's position in its orbit plane with respect to the dual GEOPAUSE satellite system, and hence relative to the Earth's center. One then should have the radial distance of from the altimeter to the Earth's center with an accuracy which is within about a factor of two of the accuracy of the knowledge of the radial distance of the GEOPAUSE satellites. This, in turn, should not be far from the decimeter accuracy capability of the laser and electronic ranging systems.

The period of the altimeter satellite will be on the order of an eighth of the period of the GEOPAUSE satellites, hence the prime coverage arc will advance about 45° along the orbit during each revolution of the altimeter satellite. The prime coverage arc will also be displaced some twenty-four degrees or so in longitude from one revolution to the next. By suitably choosing the period commensurabilities of the GEOPAUSE and altimeter satellites, it should be possible to obtain good coverages of the sea surfaces in reasonable times.

C. Geopotential Studies

The same orbit plane of the two GEOPAUSE satellites is the ideal one for the orbit of the low altitude drag free satellite which will sense the geopotential. Range rate observations made between each of the GEOPAUSE satellites and such a low altitude drag free satellite give two orthogonal velocity components, in the common orbit plane, relative to the GEOPAUSE satellites. One then obtains directly and simultaneously the two most important velocity, quantities, i.e., the radial and along-track components.

Radial component derivatives give accelerations directly which can tell us about mass anomalies, or mascons. The along track component is also a sensitive indicator of gravitational perturbations. The position and velocity accuracies which should be attainable with the GEOPAUSE satellite using range and range rate tracking data having accuracies at the decimeter and 0.05 mm/sec levels, respectively, are consistent with the goal of obtaining satellite-to-satellite tracking data at the 0.05 mm/sec level. This, in turn, will be the basis for determining the geoid with decimeter accuracy.

The system consisting of the Geopause spacecraft and the Drag-free satellite will be able to sample the along-track and radial velocity components over the entire earth with a resolution which is comparable to the Drag-free satellite altitude. For example, if the Drag-free satellite's mean height is 300 km, the spatial resolution will be of the order of three degrees. Ground tracks of the Drag-free satellite separated by 300 km. could be revisited or nearly revisited about at intervals of a little over a week. Roughly speaking, about half of each 45-minute pass of the Drag-free satellite beneath the Geopause spacecraft, i.e., the half centered on the sub-Geopause point, can be associated with the radial velocity component. The remaining half, consisting roughly of the two ten-minute wings near the limbs, can be associated with the along-track velocity component. Thus, a complete survey of the earth with respect to these 2 velocity components can be arranged by properly choosing the commensurabilities between the Drag-free and Geopause satellite orbits. This might be done, for example, in such a way that, each time a Drag-free satellite ground track is revisited, the sub-Geopause point is a quarter of a revolution from its position in the previous corresponding visit to that track.

One could view the coverage pattern configurations alternatively by noting that the sub-Geopause coverage arc advances about 45° or so during each revolution of the low altitude Drag-free Geosense satellite. The Geopause ground track is, accordingly, well sampled gravitationally by the Geosense satellite. A network of Geopause ground tracks separated by three degrees can be traced out in about two and a half months, making possible a complete survey of the gravitational field. A survey having finer resolution would take correspondingly longer.

Satellite-to-satellite tracking between a Drag-free satellite and a geostationary satellite such as ATS-F or ATS-G, for example, will not provide this type of coverage. Even if an ATS were to drift around the equator, which could involve ground station complexities, the resulting tracking would yield no information about along-track velocity components near the equator, and no information about radial velocity components near the poles.

A spacecraft of the Geopause type is, therefore, essential if the true potential of the Drag-free satellite for sensing the geopotential is to be realized. In other words, a complete geopotential sensing system will consist of a Drag-free satellite and a Geopause satellite in orbits which are selected as a matched pair.

The GEOPAUSE satellite system thus should be able to make key contributions in connection with both of the major problems of space oceanography. These are the determination of the positions of the geoid and the sea surface independently, but relative to the same reference system, with accuracies reflecting the tracking system capabilities. The important oceanographic information will be found in the height differences between these two surfaces, i.e., the sea surface and the geoid.

D. Spacecraft Systems

1. The Drag-free Satellite and the Low Altitude Observatory Spacecraft Systems

Effects of higher order geopotential terms are functions of corresponding powers of the radius. In order to improve the ability to study these terms, it is desirable to orbit the spacecraft at the lowest practical altitudes. Drag-free technology will be useful here. The orbit should be nearly circular to permit sensing of the geopotential over most of each revolution. The optimum choice for eccentricity will be made on the basis of an appropriate study of the various factors including the sensitivity of the orbit to perturbations, practical lifetime considerations, etc. The orbit will be polar to permit sensing the entire gravitational field of the earth.

The geopotential varies relatively slowly, hence it will probably be sufficient during the first mission to conduct a survey of the geopotential involving possibly a couple of complete revolutions of the perigee. Hence a lifetime of the order of half a year would be suitable. Long term variations would be studied by sampling the geopotential at appropriate intervals which might be several years in length, say. The timing would probably also be a function of the rate of advance of the state of the art.

The low altitude drag-free satellite instrument complement should include an altimeter and perhaps a gradiometer in order to provide measures which can be correlated with the satellite-to-satellite tracking data, and used in the geophysical analyses, too.

The low-altitude drag-free satellite will also constitute an ideal platform for sensing the geomagnetic field for the same reasons as in the case of the gravitational field. The low altitude drag-free satellite should, accordingly, include an appropriate magnetometer system.

The drag-free satellite will possess, intrinsically, the capability to obtain deceleration data. Experimental equipment designed to observe atmospheric structure paramters can thus provide correlative data to aid in the evaluation of the drag-free system itself. From the scientific standpoint, the opportunity to observe the atmosphere in the 250 to 350 km altitude region, i.e., near the ionospheric F_2 maximum level, over the whole of the earth for extended time intervals is an especially valuable one, as S. Bauer has pointed out.(5) Such a satellite will provide a natural complement to the Atmosphere Explorers C, D and E since it will permit the separation of time dependent effects from those which depend on latitude and/or local time (rt.asc.). It will not be possible to do this over extended periods using the orbits of the Atmosphere Explorers. Bauer has suggested, for example, that measuremments of density and temperature could be made with the aid of a nitrogen mass spectrometer in a rotating configuration. The instrument senses density in the ram direction, and temperature information can be derived from readings near the point where the gage orifice direction is normal to the relative wind velocity vector.

The low-altitude drag-free satellite is an ideal one in which to conduct ionospheric experiments since it orbits at about the F_2 maximum level.

The drag-free satellite thus can logically evolve into a Low Altitude Observatory Spacecraft System.

2. <u>The Altimeter Satellite System</u>

The use of a satellite altimeter to study ocean surface phenomena is expected to involve the making of synoptic observations since the ocean surface presents a relatively high degree of variability with time, when compared with the geopotential, for example. Accordingly, the ideal satellite orbit for altimetry purposes is one allowing a long operational lifetime, i.e., one which is above the main drag region. The orbit should be as low as this constraint permits in order to maximize the effectiveness of the radar. An altitude of the order of seven hundred kilometers appears to be a good compromise.

This satellite is a logical platform from which to look at other aspects of the ocean surface in order, again, to make as many correlative measurements as is practicable. Observing programs to give temperature and sea state data at other frequencies, and even studies in the visible wavelength region of the incidence of foam, say, could provide data which would be of great value both in themselves and in connection with the interpretation and analysis of the altimeter measures.

Thus, the synoptic altimeter satellite, too, can logically evolve into an Observatory Spacecraft.

3. The Geopause Spacecraft

The Geopause spacecraft would be equipped with laser corner reflectors and electronic range and range rate tracking systems having accuracies of the order of a decimeter and 0.03 mm/sec, respectively. The range and range rate systems would be used to track the Geopause spacecraft from the fundamental stations, and to track the Drag-free and altimeter satellites from the Geopause spacecraft. A gravity gradient system could be used to provide stabilization for the Geopause spacecraft. A high gain antenna would be needed for the satellite-to-satellite tracking link. It could be constructed using a mesh-like material which reflects microwaves but presents a small net surface to interact with radiation pressure. Such materials have been studied in connection with the passive communication satellite program. Cf. Figure 7.

The first Geopause spacecraft would have two principal objectives. It would serve as the high-altitude one of the pair of spacecraft, the other being the drag-free spacecraft, which would complete a survey of the entire gravitational field of the earth. It would also provide the first real opportunity to attempt to realize the full potential of the laser and electronic range tracking systems having decimeter accuracy capability. It will, too, be of real value in connection with the intercomparison and calibration of these systems on a continuing basis. Up to now it has been customary to calibrate geodetic electronic ranging systems, i.e., to determine their biases, by comparing their results, ultimately, with those based on reference optical data. One has, in effect, made use of the fact that, in the case of the optical systems developed by astronomers, the biases have been reduced to very low levels through centuries of painstaking effort. Laser and electronic ranging systems can no longer be calibrated by taking this easy path, however, since their potential accuracy capabilities exceed those of the proven optical systems. Accordingly one faces perhaps for the first time, really, in general geodetic work, the problem of removing the biases in some other way.

The Geopause spacecraft can be of real value in this connection since it will provide the opportunity for simultaneous range observations by four or more stations on a number of occasions on a more or less continuing basis. Thus, for the first time, continuing calibration and identification of biases in the ultra-precise ranging systems will become practical.

Orbit determination results from Geopause I would also provide the basic information needed to decide whether follow-on Geopause spacecraft should be at the same altitude as Geopause I, or at some other height.

As indicated earlier, a pair of Geopause spacecraft and an altimeter satellite can constitute a basic scientific and applications investigatory system for oceanographic studies. Four Geopause spacecraft in the same orbit separated by a quarter of a revolution, together with one or more altimeter spacecraft, could provide coverage on a much more rapid basis since the altimeter satellites are viewed continuously by such a Geopause system. This means that an altimeter satellite could map the sea surfaces over the entire Earth with twelve degree resolution in a single day, or with one degree resolution in twelve days. Improved resolution for a daily survey could be obtained by adding to the number of spacecraft in the Altimeter satellite "track". Two such satellites would give six degree resolution, four would give three degree resolution, etc. Such a Geopause Altimeter Oceanographic system could provide data having great value from both the scientific and applications standpoints.

Tracking between the different Geopause spacecraft can be accomplished using the range and range rate tracking systems in the manner discussed in reference 6 in connection with the SCOTT Network. The range and range rate systems could be of the electronic and/or the laser type. Consideration is already being given, for example, to the use of a laser system for range and range rate tracking between ATS-F and ATS-G. Tracking of low altitude spacecraft from the Geopause spacecraft might also be done by means of laser systems as Vonbun has pointed out. The use of a mirror to direct the laser beam may simplify the control system requirements. It might even turn out that the high-gain microwave antenna would not be needed.

Each set of spacecraft consisting or one or more Geopause spacecraft and one or more Drag-free and/or altimeter spacecraft should be viewed from the beginning as a matched set from the standpoints of orbit selection, commensurability considerations, etc.

The more advanced Earth Physics and Geodesy systems thus tend increasingly toward the use of sets of spacecraft as well as single satellites. In looking at different ways to achieve a given result it is possible to consider the relative merits both of individual spacecraft and of different sets of spacecraft. Thus, some of the functions which can be performed by the Geodynamics, LAGEOS, MiniGEOS or SCOTT spacecraft systems might also be performed, in different combinations at times, by Geopause and Drag-free altimeter spacecraft. (Cf., references 1, 6, and 7.) Considered as individual spacecraft, for example, the Geodynamics, LAGEOS and Geopause satellites could each be used to determine station locations and associated Earth motions, with some variations in approach due to differences in the orbit heights. Considered as one of a set of spacecraft, a Geopause satellite could also be used in connection with the satellite-to-satellite tracking of Drag-free altimeter spacecraft. The potentialities of various spacecraft thus depend partly on the ways in which they might fit into larger systems.

It is anticipated that the GEOPAUSE satellite could be useful in connection with Geodesy, Earth physics, Oceanography, Polar motion, Altimetry, UT 1, Sea surface, and Earthquake studies.

The Geopause Spacecraft System also has potential as a Tracking and Data Relay Satellite System. It could be especially valuable in connection with programs of the EOS type, for example, both because of its polar coverage capability, and since it provides the key to meeting the stringent orbital accuracy requirements associated with such spacecraft.

E. Central Elements of a Unified Earth Physics and Geodesy System

The principal elements of the Unified Earth Physics and Geodesy System which interrelate strongly with one another have been discussed. These central elements are:

1. VLBI
2. Geopause Spacecraft
3. Drag-free Geosensing Spacecraft
4. Altimeter Spacecraft
5. Geodynamics spacecraft
6. Lunar Laser and Beacon Systems
7. Lunar & Planetary Spacecraft

Their key features and interrelationships can be summarized briefly, as indicated in Tables VI through XI, in terms of the principal investigations and determinations which are contemplated in connection with them. Investigations which the Geopause spacecraft can contribute to are listed in Tables VII through IX. Investigations involving the Geodynamics spacecraft are the same as the ones listed in Table VII, with the exception of item C which involves electronic equipment not contained in the Geodynamics satellite. An advanced version of the Geodynamics spacecraft might be placed in the Geopause orbit plane and tracked from the Geopause spacecraft.

III. PLANS AND STUDIES

A plan for the Earth Physics and Geodesy Program as a whole is described in reference 1. Studies and/or plans are being prepared in connection with specific aspects of the program. These include a study of VLBI from the standpoint of the Manned Space Flight Network, a plan for conducting VLBI experiments in connection with ATS spacecraft, a study pointed toward selection of sites for investigating crustal motions, and a Satellite Radar Altimeter Development Plan. (8-13, 15, 16)

It is recommended that a phase A study be initiated to consider as a matched, unified set the Geopause, Drag-free, and altimeter spacecraft. The study should include consideration of the associated laser and electronic range and range rate tracking systems having accuracy capabilities in the decimeter and 0.03 mm/sec ranges, respectively. The study should take into account the inventory of existing lasers and possible modifications to them which could reasonably be expected to be available by the time the Geopause spacecraft fly. Similar remarks apply to proposed laser equipment. The use of a hydrogen maser in the high altitude satellite in connection with satellite-to-satellite range rate tracking, which has been proposed by G. Weiffenbach of SAO, should be considered in connection with the Geopause spacecraft satellite-to-satellite tracking system.

It is also recommended that the Gravity Gradient Stabilization Experiment once approved for ATS-F be reconsidered for ATS-F or ATS-G. It has been dropped since a control jets system does the same job for less weight. The new factor here, as H. Gerwin has pointed out, is the fact that the Geopause spacecraft should be stabilized with an earth-pointing face without the orbit perturbing side effects of control jets (14). A gravity gradient system would, accordingly, be a better choice for the Geopause spacecraft.

It is a pleasure to express appreciation to C. A. Wagner and J. G. Marsh for discussions and assistance in connection with computing relating to gravitational perturbations of satellites at large distances and tracking station locations.

Table I

A Fundamental Station Network
for a Unified Earth Physics and Geodesy Program

Rosman
Goldstone
Santiago
Madrid
Joburg
Kashima
Orroral
Alaska
Hawaii

Table II

A Typical Set of Stations for a

One-dimensional Plate Motion Study

Hawaii

Goldstone

Alaska

Kashima

Guam

Orroral

Table III

A Typical Set of Stations for a

Three-dimensional Plate Motion Study

Rosman
Goldstone
Haystack
Alaska
Madrid
Onsala
Manchester
Cambridge
Crimea

Table IV

NASA GODDARD STATIONS HAVING POTENTIAL IN CONNECTION WITH EARTH PHYSICS AND GEODESY PROGRAMS

Rosman	Carnarvon
Goldstone	Tananarive
Santiago	Ascension
Madrid	Grand Canary
Joburg	Antigua
Orroral	Bermuda
Hawaii	Grand Bahama
Alaska	Cape Kennedy
Guam	Corpus Christi
Canberra	Guaymas
Quito	Winkfield

Table V

POLAR MOTION AND LATITUDE
SERVICE STATIONS
AT 39°8' NORTH LATITUDE

Japan
Turkestan
Sardinia
Maryland
California

Table VI

VLBI

INVESTIGATIONS

I. Fundamental Station Locations and Motions Relative to Inertial Reference System of Radio Sources, including

- A. Dynamical Motions
  1. Precession & Nutation
  2. Polar Motion & UT 1
- B. Crustal Motions
  1. Interplate Motions
     - a. 1-dimensional
     - b. 3-dimensional
  2. Intraplate Motions
     - a. Deformations Associated with Faults in Far Zones, e.g., Project SAFE
  3. Earthquakes

Table VII

GEOPAUSE SPACECRAFT
INVESTIGATIONS

I. Relative Positions and Motions of Geopause Spacecraft & Fundamental Stations Including
   - A. Fine Structure of
     - 1. Dynamical Motions
       - a. Polar Motions
       - b. UT 1
     - 2. Crustal Motions
       - a. Interplate Motions
         - i. 1-dimensional
         - ii. 3-dimensional
       - b. Intraplate Motions
         - i. Deformations Associated with Faults in Far Zones, e.g., Project SAFE
       - c. Earthquakes
     - 3. Correlations of Earthquakes with Polar Motions
   - B. Earth's mass and radius
   - C. Intercomparison of Laser and Electronic Ranging Systems

Table VIII

DRAG-FREE SATELLITE AND GEOPAUSE SPACECRAFT SYSTEM INVESTIGATION

Geopotential and hence Geoid from

Along Track & Radial Velocity Components of

Drag-free Satellite Relative to Geopause Spacecraft

Obtained over Entire Earth With

Resolution Comparable to Drag-Free Satellite Height

Table IX

ALTIMETER SATELLITE AND GEOPAUSE SPACECRAFT SYSTEM INVESTIGATIONS

I. Two In-plane Components of Altimeter Satellite Position Relative to Two Geopause Spacecraft Give Radial Distance from Earth's Center of Altimeter & hence Ocean Surface

II. A System of Four Geopause Spacecraft Gives, Continuously, Radial Distance of Altimeter & Ocean Surface

Table X

LUNAR LASER AND BEACON
INVESTIGATIONS

I. Relative Positions and Motions of Lunar Laser Corner Reflectors & Beacons and Laser & VLBI Sites on Earth give
   A. Lunar Motions Including
      1. Dynamical Motions
         a. Lunar Ephemeris
         b. Lunar Librations
      2. Surface Motions, e.g., Near Faults
   B. Earth's Motions Including
      1. Dynamical Motions
         a. Precession & Nutation
         b. Polar Motion and UT 1
      2. Crustal Motions
         a. Interplate Motions
            i. 1-dimensional
            ii. 3-dimensional
         b. Intraplate Motions
            i. Deformations Associated With Faults in Far Zones, e.g., Project SAFE
         c. Earthquakes

Table XI

LUNAR AND PLANETARY SPACECRAFT
INVESTIGATIONS

I. Tracking from Fundamental Stations
   Contributes to Determinations of
   - A. Gravitational Quantities
     1. GM for Earth, Moon, & Planets
     2. Harmonic Coefficients of Potential for Moon & Planets
   - B. Geometrical Quantities
     1. Earth Radius
     2. Lunar Distance
     3. Astronomical Unit

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A TYPICAL FUNDAMENTAL NETWORK

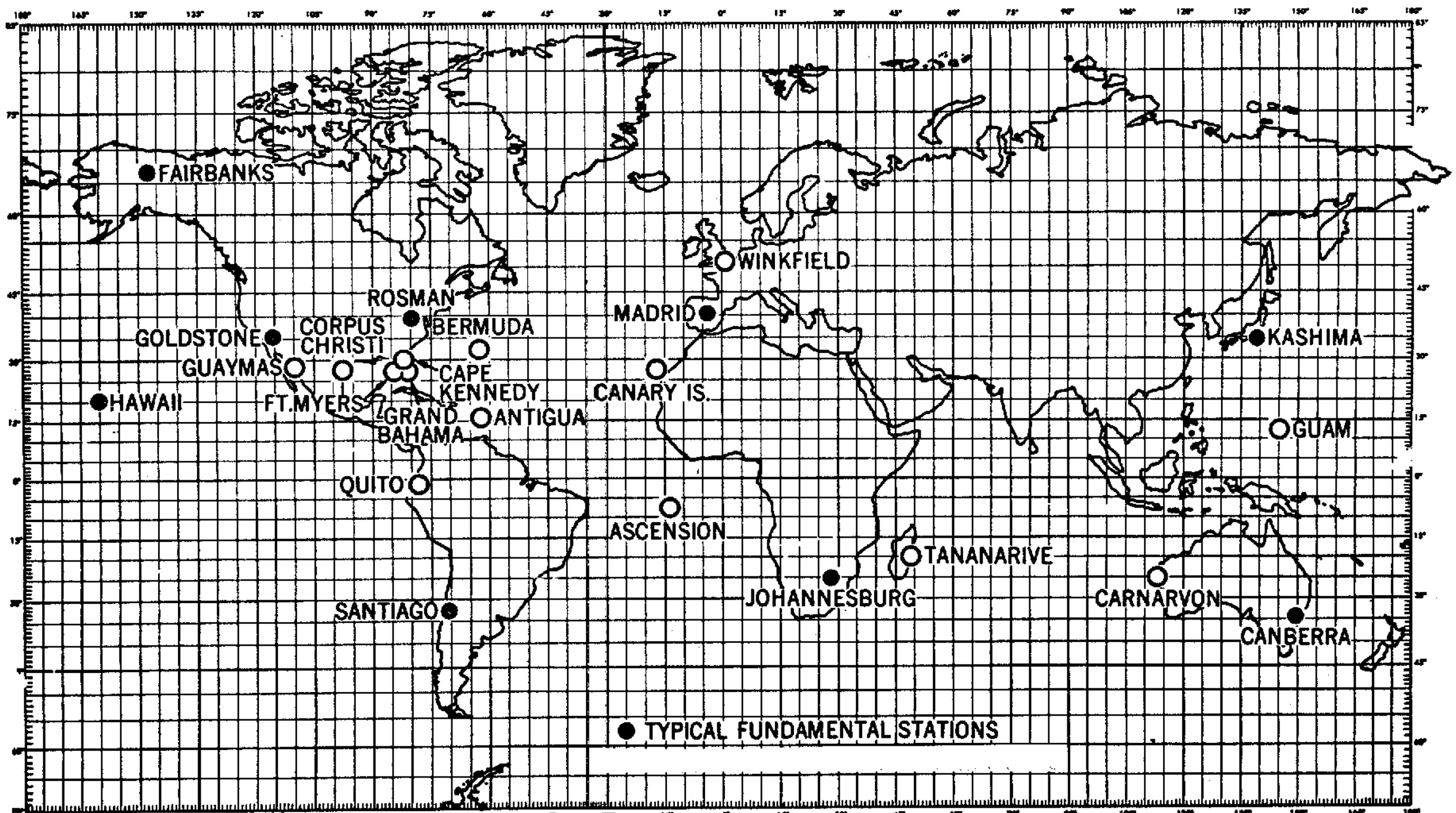


Figure 1

35

36

A TYPICAL FUNDAMENTAL NETWORK

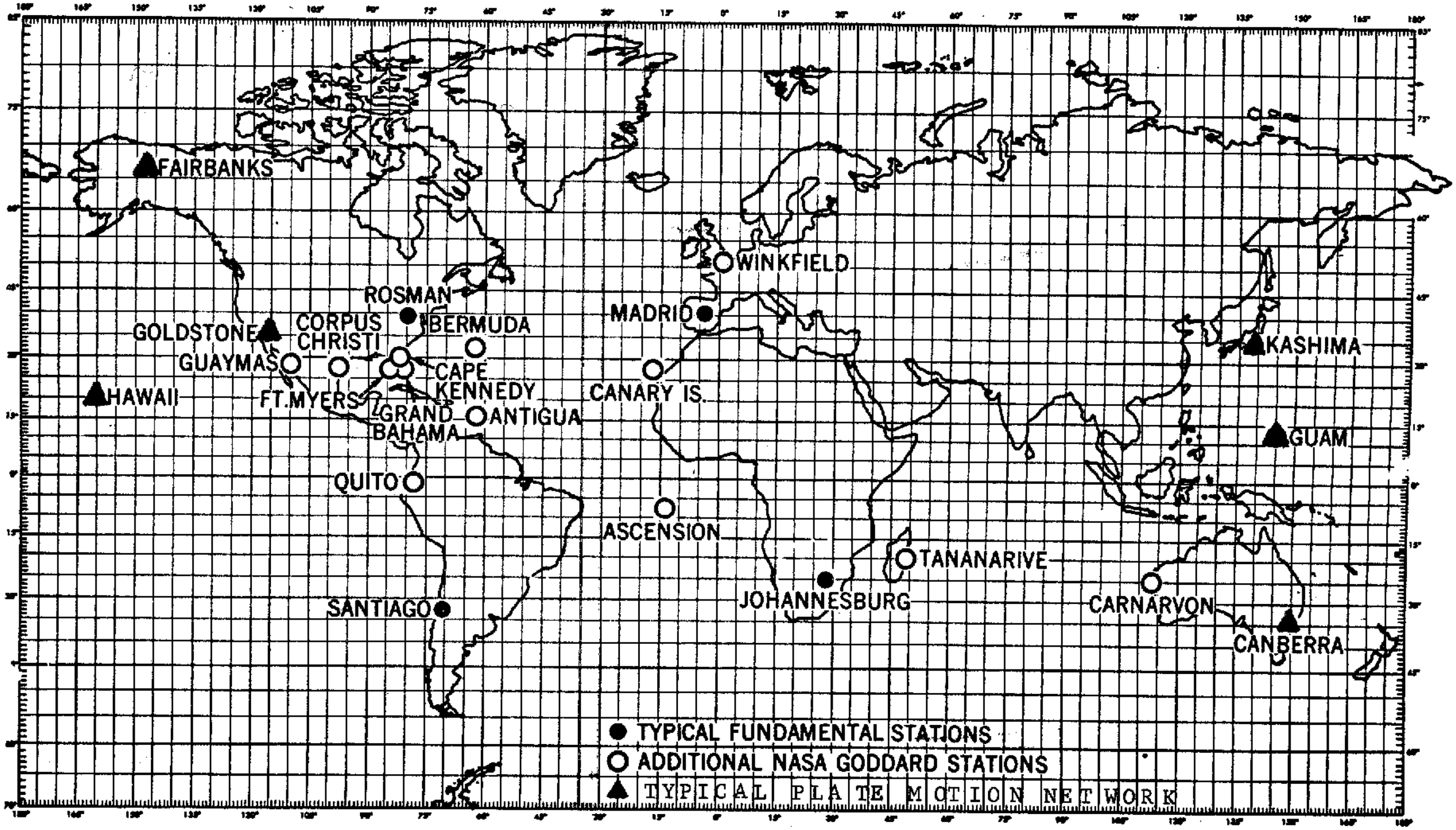


Figure 2

A TYPICAL FUNDAMENTAL NETWORK

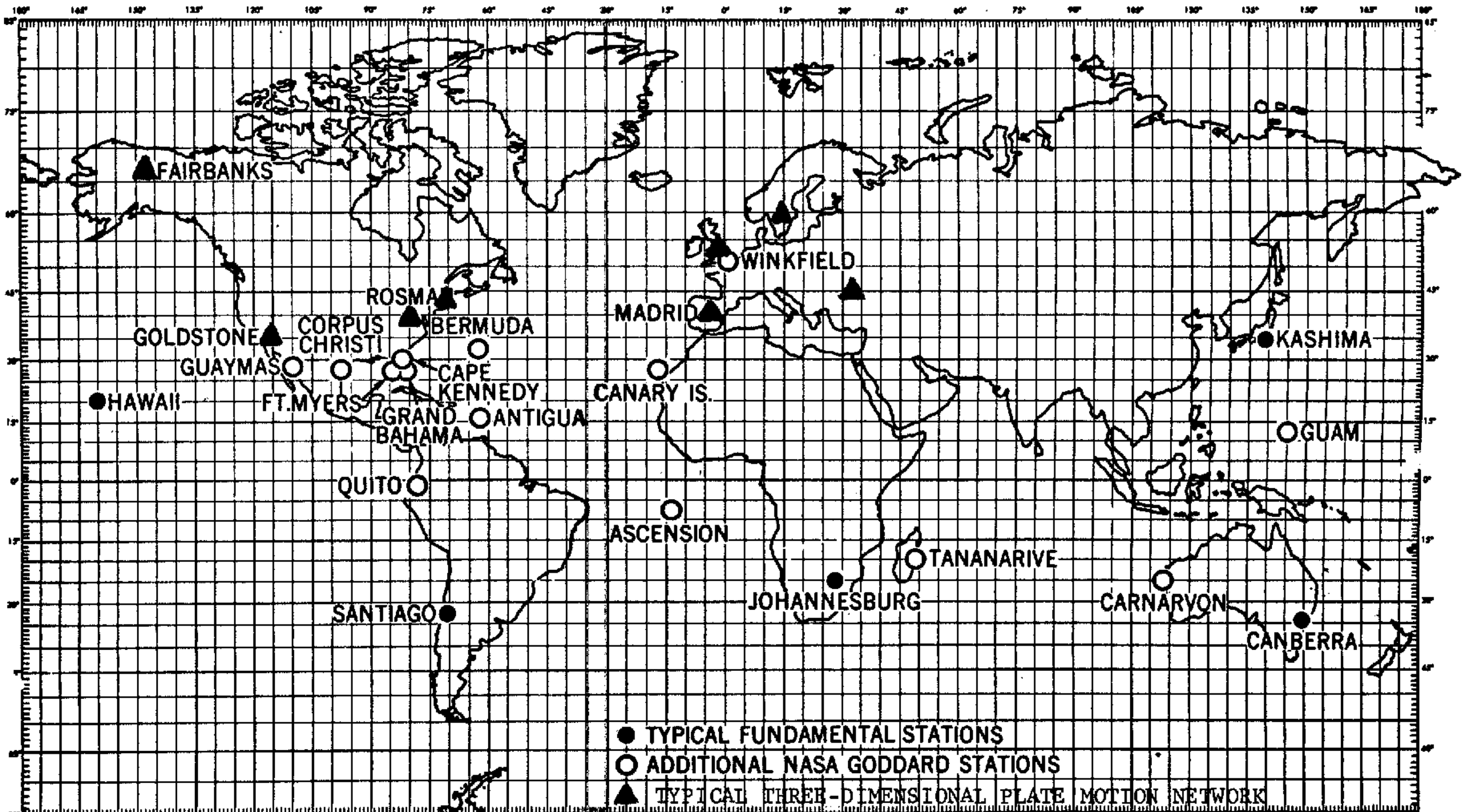


Figure 3

A TYPICAL FUNDAMENTAL NETWORK

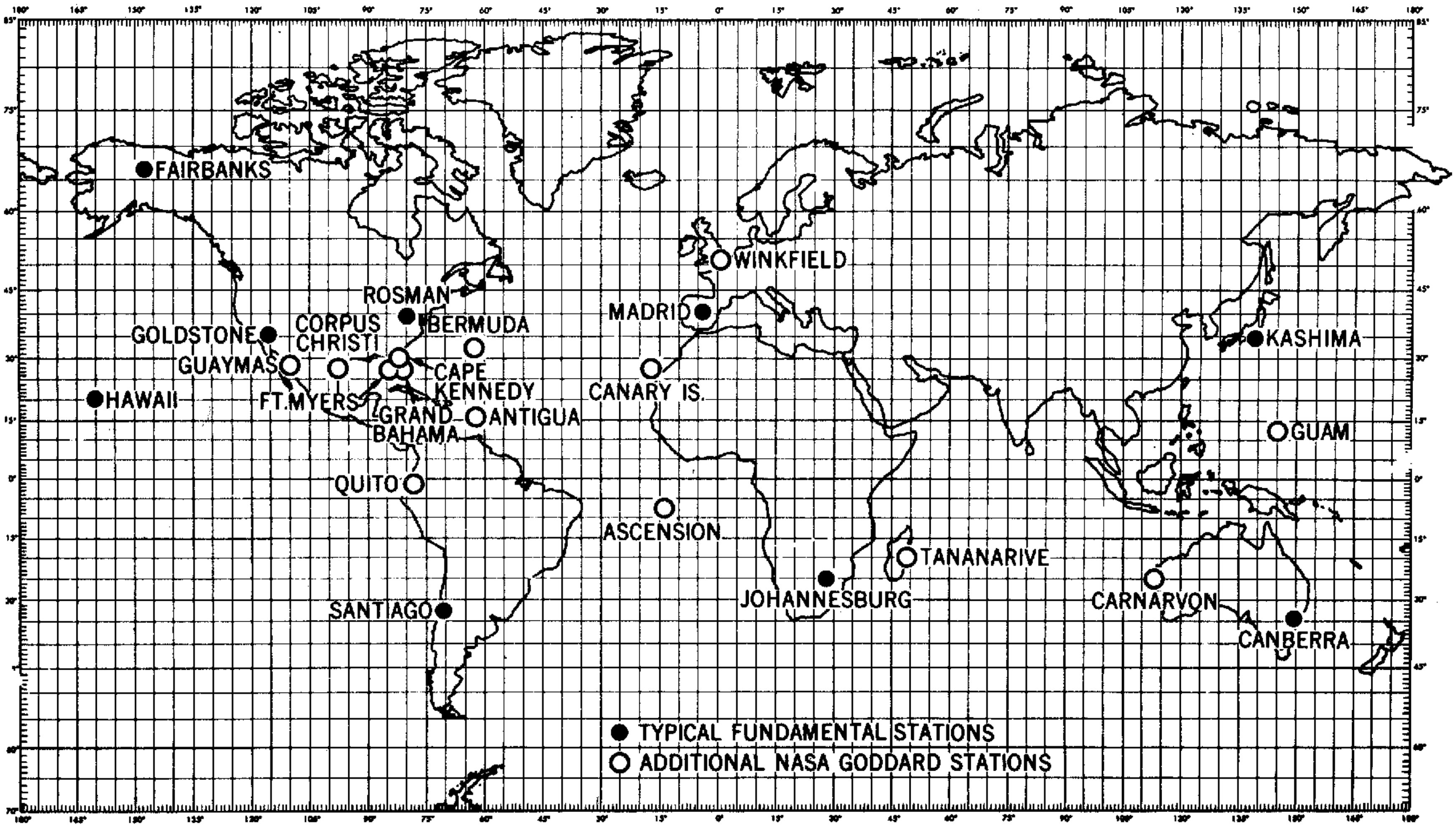


Figure 4

A TYPICAL FUNDAMENTAL NETWORK INDICATING POLAR MOTION COVERAGE

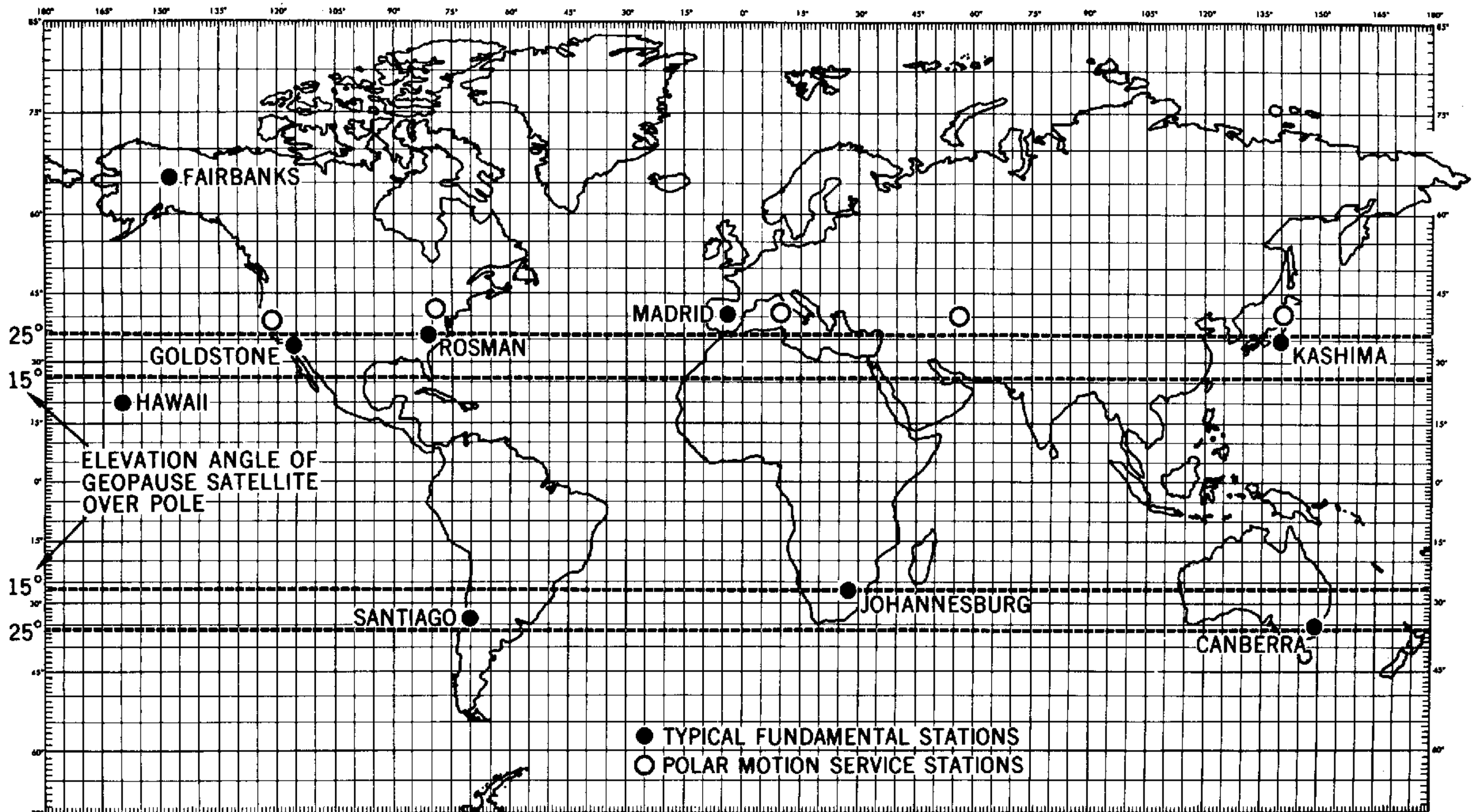
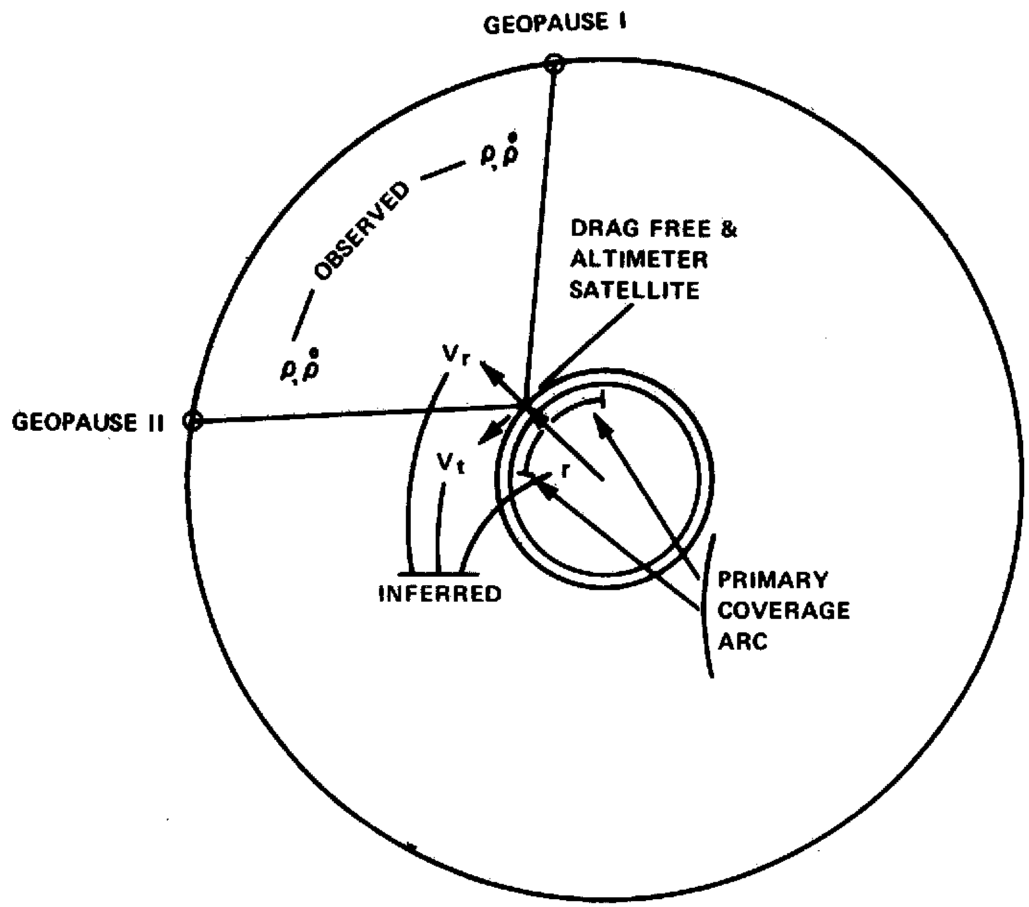


Figure 5

GEOPAUSE
DRAG FREE & ALTIMETER SPACECRAFT
SATELLITE-TO-SATELLITE TRACKING



PRIMARY COVERAGE ARC MOVES ABOUT 24° LONGITUDE

AND 40° IN LATITUDE EACH REVOLUTION

Figure 6

40

GEOPAUSE SPACECRAFT CONCEPT

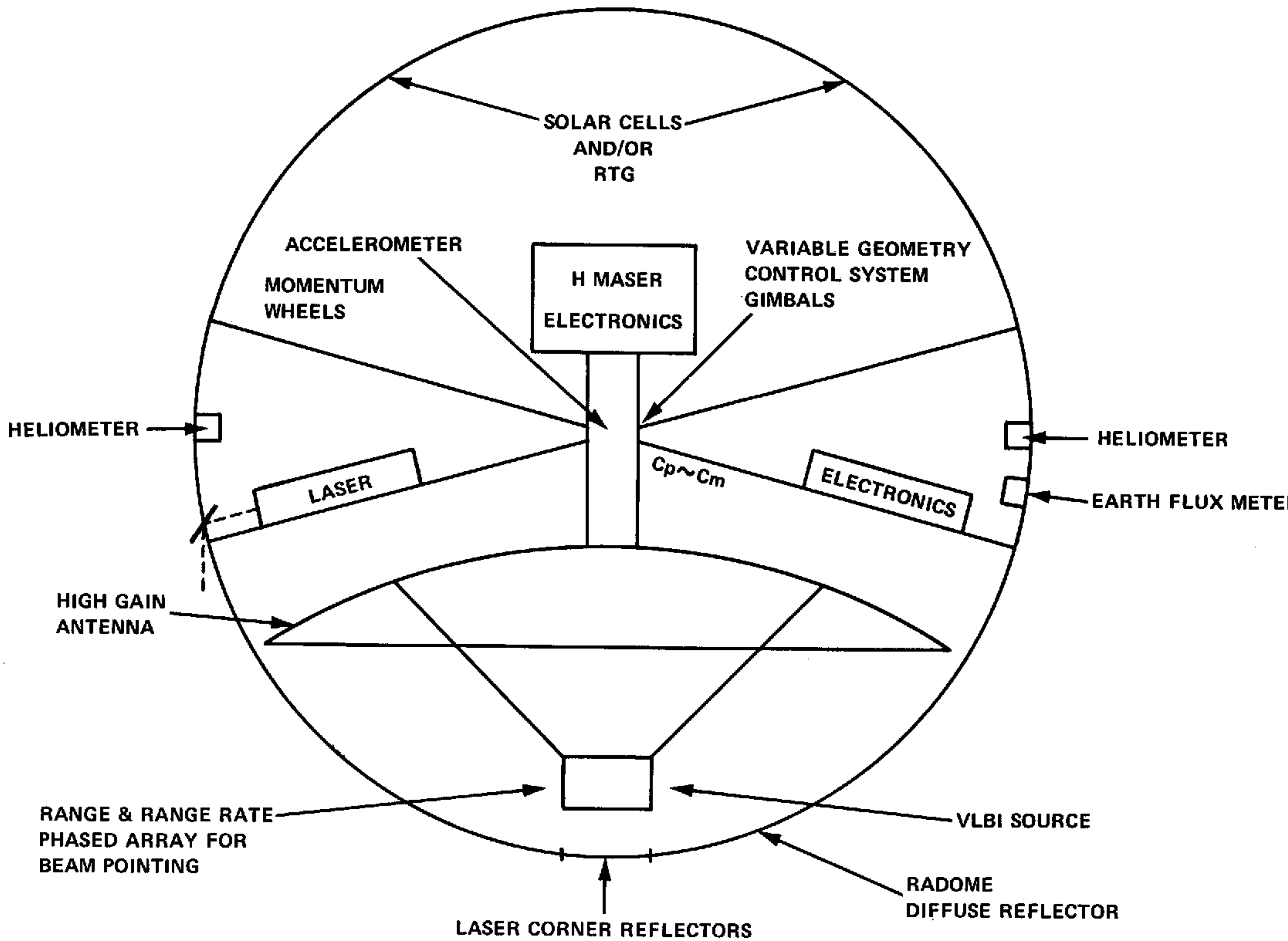


Figure 7